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HEAT RELEASE RATE, PERFORMANCE AND VIBRATION ANALYSIS OF DIESEL ENGINE OPERATING WITH BIODIESEL - TRIACETIN ADDITIVE BLEND FUELS

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ABSTRACT

The diesel fuel experiments were conducted on diesel engine, with coconut oil methyl ester (COME)-Triacetin additive blends as alternative fuels. Reduction of CO_2, CO, HC, NO, and smoke emissions were achieved successfully with 10% Triacetin and 90% COME blend fuel. Three directions of engine cylinder and on the foundation were measured and analyzed for Vibration of engine, to elicit information about the nature of combustion in the cylinder. The pressure signatures were tallied with the time waves, eliminating the time lag in between exciter and vibration of cylinder head. Triacetin, being an antiknock fuel with 10% blend, emanated as the best blend fuel with its contribution to reduce cylinder vibration in the vertical direction. Time wave resemblance with pure harmonics indicates smooth combustion with lesser engine detonation. By analyzing the measured in-cylinder pressure data and released heat rate, it is observed that the addition of Triacetin increases the ignition delay and the amount of heat release in the premixed combustion duration, but shortens both the diffusive burning duration and the total combustion duration.

***KEYWORDS:** Biodiesel, Engine Performance, Triacetin, Vibrations, Additive, Blend fuel & Heat Release Rate*

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Original Article

INTRODUCTION

In lieu of the rapid depletion and the price hike of fossil fuels, researchers concentrated to search for alternative fuels for higher efficiency with additives. Ethanol and methanol are proved to be more effective alternative fuels for internal combustion (I C) engines. High amount of oxygen content in methanol and ethanol helps to make complete combustion with atmospheric oxygen. DME with oxygen content of 34.7% by weight is noticed as one of the promising alternative fuel additive for IC engines, recently. DME can be produced from natural gas, coal or even from biomass sources of energy. Emissions including THC, smoke, carbon dioxide and NO_x decreases with DME additive, while slight increase in CO noticed when compared to the conventional diesel fuel. Lower exhaust emissions were mostly due to the presence of high amount of oxygen in DME, short ignition delay, C-C bond absence and vaporization of DME, instantaneously [1].

Biodiesel with 10% Triacetin blend fuel combination proved encouraging results in all respects of performance, including vibrations and emissions of the C I engine [2, 3]. Due to higher cetane number and oxygen content in DEE additive, smoke, THC emissions decreases, lower the CO emissions at high load condition and decreases NO_x emissions with DEE-diesel blends [4]. With 5% DEE lower CO, THC and smoke emissions, a slight improvement in thermal efficiency was observed [5]. Clean combustion of diesel engines can be fulfilled, only if engine development is coupled with diesel fuel reformulation or additive introduction [6, 7]. The methods can be

adopted to reduce PM and NO_x emissions including high-pressure injection, turbo charging and exhaust after treatments or the use of fuel additives, which are thought to be one of the most attractive solutions [8]. Dimethyl carbonate presents good properties, when blended with diesel fuel and reduces smoke almost linearly with its concentration. The addition of 10% dimethyl carbonate in the diesel fuel promotes reduction of smoke up to 35-50%, and also reduces the hydrocarbons and carbon monoxide densities, but with a slight increase in NO_x emissions. The engine with dimethyl carbonate emits almost smokeless exhaust gas, because of no C-C bonds in the molecules. The trend is increasing to use blend with biomass products such as vegetable oil, ethanol or biodiesel, which increases the use of alternative fuels. Blend fuels of diesel and biodiesel usually require additives to improve the lubricity, stability and combustion efficiency by increasing the cetane number. Blends of diesel and ethanol (E-diesel) are usually requiring additives to improve miscibility and reduce knock [9]. The best peak pressure value and heat release rate was obtained for 10% Triacetin additive with biodiesel among 5, 10, 15, 20 and 25% concentrations. However, coconut biodiesel with triacetin (cetane improver) additive blend fuels the NHRR, the values do not show a clear trend, and it can be seen that some biodiesel blends perform sufficiently close to neat diesel [10].

HEAT RELEASE RATE

The cylinder pressure and crank angle signals were obtained from the data logger for the defined engine load. The data was stored in computer based digital data acquisition system for 100 cycles. No spatial variations were considered, so the model is said to be zero-dimensional. With the data obtaining for combustion cycle, the net heat release rate (NHRR) was calculated based on the first law of thermodynamics by considering average value of pressure and crank angle data [11]. The in-cylinder pressure reflects the combustion process involving piston work produced on gas, heat transfer to combustion chamber walls, as well as mass of the flow in and out of crevice regions between the piston, piston rings and cylinder liner. The combustion process propagates through the combustion chamber; each of these processes must be related to the cylinder pressure [12]. A single zone model is used based on the first law of thermodynamics (equation **1**). Where, dU is the change in internal energy of mass in the system, dQ is the heat transfer to the system and dW is the work produced by the system.

$$dU = dQ - dW + \sum_i h_i dm_i \tag{1}$$

Heat transfer in the cylinder occurs by both convection and radiation, where forced convection constitutes the major role in applications. Heat transfer by convection is the transfer of energy within the fluid due to the movement from the solid surface [13, 14]. The magnitude and rate of energy transfer by convection is $\dot{Q}_{ht}$. This occurs in the direction perpendicular to the fluid surface and can be obtained by Newton's law of cooling (equation **2**).

$$\dot{Q}_{ht} = h_c A \Delta T = h_c A (T - T_w) \tag{2}$$

Chemical Energy Release

During the combustion process, chemical energy released is calculated by using Equation (**3**). This ordinary differential equation can be solved easily by numerical methods for the net heat release rate, if the cylinder pressure rate is provided, together with an initial value for the heat release [14, 16]. Where, dQ_{ch} is the heat released due to chemical energy, dQ_{ht} is the convection heat transfer, V_{cr}, the crevice volume, T_w is the wall temperature and T is the temperature of gas flow

out of the crevice volume.

$$\begin{aligned} dQ_{ch} &= \frac{1}{\gamma-1}Vdp + \frac{\gamma}{\gamma-1}pdV + dQ_{ht} + (c_v T + RT'\left(1+\frac{1}{\gamma-1}\right))\frac{V_{cr}}{RT_w}dp \\ &= \frac{1}{\gamma-1}Vdp + \frac{\gamma}{\gamma-1}pdV + dQ_{ht} + (\frac{1}{\gamma-1}T + T'\left(1+\frac{1}{\gamma-1}\right))\frac{V_{cr}}{T_w}dp \end{aligned} \quad (3)$$

EXPERIMENTAL SETUP

For the present experimental work, a four stroke single cylinder diesel engine was used. Biodiesel was prepared from coconut oil with methanol by transestirification process [17, 18]. Blend fuels were prepared with coconut oil methyl ester at different percentages (75%, 80%, 85%, 90%, 95%, and 100%) and triacetin additive (25%, 20%, 15%, 10%, 5% and 0%) by volumes. The dynamometer control panel was used to change the load on the engine. On the spring balance, 40kg is the full load, which is considered as 100 percent load on the engine. The dynamometer is stable and works consistently even in the case of minor variation in engine speed and engine vibration. The experiments were conducted at 0, 25, 50, 75 and 100 percent of load on the engine at the rated speed of 1500 RPM.

The observations were recorded in number of times to get reasonable reading values. Engine cylinder vibration was monitored in FFT form at each load for all blend fuels in order to compare the cylinder excitation frequencies with the frequencies of diesel oil. Time wave forms on the cylinder head are also recorded to analyze engine combustion. Engine cylinder vibrations are measured by FFT and time waveforms. These forms represent the combustion intensity in the cylinder. The vibration accelerometer was mounted on cylinder head, preferably with bolt connecting to the head of engine cylinder, in order to record the engine vibrations by using DC-11 data logger, which directly gives the spectral data in the form of FFT and overall vibration levels. Recorded FFT data was collected with the help of On-Time Windows based software. The Time waveforms were obtained on the cylinder head by DC-11 in the OFF-ROUT mode, and are presented in graphic form by Vast-a doss based software. To assess the engine vibration, four strategic points on the engine cylinder body and the foundation were chosen. Thèse four points are

- Vertical direction on the cylinder head top,
- Radial direction on the cylinder and parallel to the axis of crank shaft,
- Radial direction on the cylinder and perpendicular to axis of the crank shaft and
- On the foundation of engine.

The recorded vibration data at all these four points encompasses the engine vibration level in the vertical direction, in the two horizontal directions or transmitted to the foundation of engine, respectively. With the help of an accelerometer vibration data was recorded. The simple diagram of experimental setup is shown in Figure **1**. The cumulative heat release rate (CHRR) and net heat release rate (NHRR) generated data was measured for pressure vs. crank angle and presented in the form of graphs. These experiments are aimed at optimizing the percentage of triacetin additive in the blend fuel for long term operation of the engine with minimal vibration. The obtained results were compared with the characteristics of neat diesel oil fuelled engines as well as COME biodiesel.

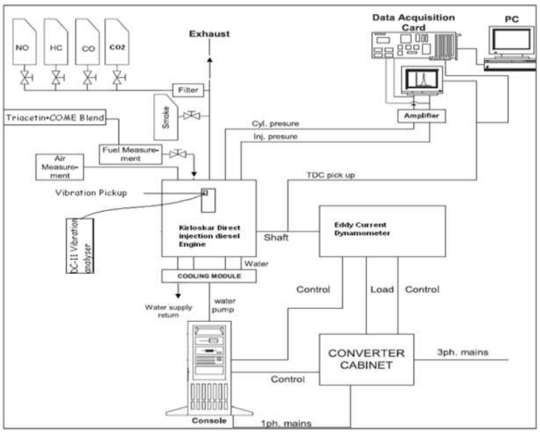

Figure 1: Line diagram of Experimental Setup

RESULTS AND DISCUSSIONS

Combustion Heat Release Rate Analysis

The cumulative and net heat release rate graphs at full load and 75% full load are shown from figures **2** to **5**. It can be observed that the net heat release rate peak is increasing with the increase of triacetin in the blend fuel. The 10% Triacetin blend falls in between the diesel and biodiesel in the net and cumulative heat release rate aspects emerges as the best alternative to the conventional diesel fuel. The cumulative heat release rate graphs decipher consistent performance both in the premixed and diffused combustion zones for 10% triacetin blend fuel with biodiesel. The 5% triacetin joins the band wagon of 20% and 25% triacetin blend fuels with respect to the low profile diffused combustion. From the figures **6** and **7,** the observation is that maximum cumulative heat released at full load and net heat release is less due to more heat transfer to cylinder surface at that load, as compared to 75% load on the engine.

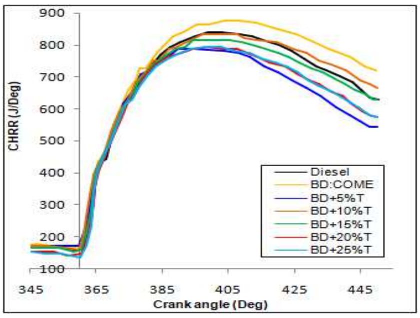

Figure 2: CHRR vs Crank Angle at Full Load

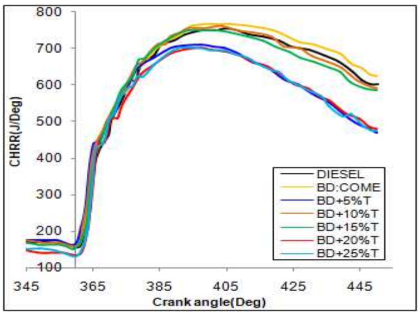

Figure 3: CHRR vs Crank Angle at 75% Load

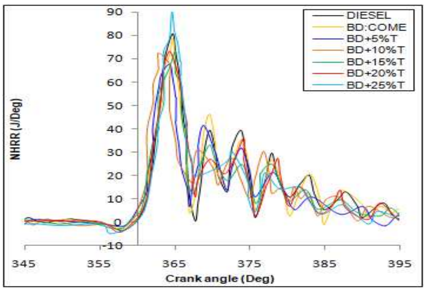

Figure 4: NHRR vs Crank Angle at Full Load

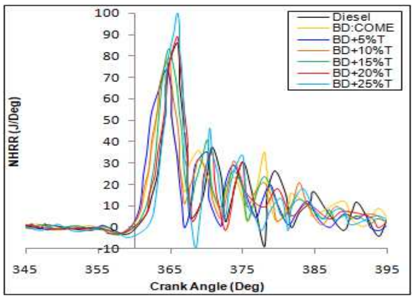

Figure 5: NHRR vs Crank Angle at 75% Load

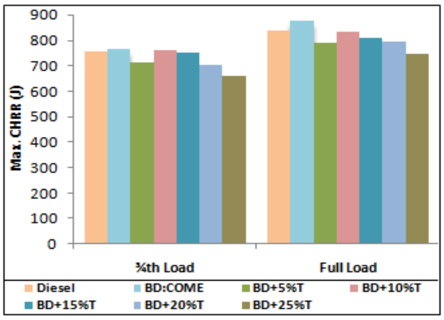

Figure 6: Max. CHRR Variation in 75% and Full Load

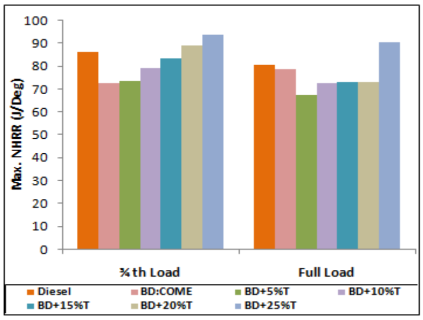

Figure 7: Max. NHRR Variation in 75% and Full Load

In the case of 10% triacetin blend fuel, the ignition delay is decreased, as this blend fuel is optimal in reducing vibrations and to improve combustion quality of engine. Heat release rate curves computed indicates better performance in case of 10% triacetin blend fuel in premixed as well as diffused zone. With increase in triacetin quantity in the blend fuel, deterioration of diffused combustion has taken place. The 5% triacetin blend fuel could not gain sensible heat from the air - fuel mixture and converse is true for the 10% blend fuel. This trend can be observed from the pressure crank angle diagrams as shown in figures **8** to **11**. There is dramatic change in the process, the coefficient with percentage of triacetin mix, especially at 5% and 10% which affects the C_p and C_v values. The cumulative heat release rate curves also exhibit the same in case of 5% and 10% triacetin blend fuels with an advantage to 10 % triacetin blend fuel in diffused combustion zone. There is a rapid fall of heat release rate in case of 5% triacetin additive blend fuel.

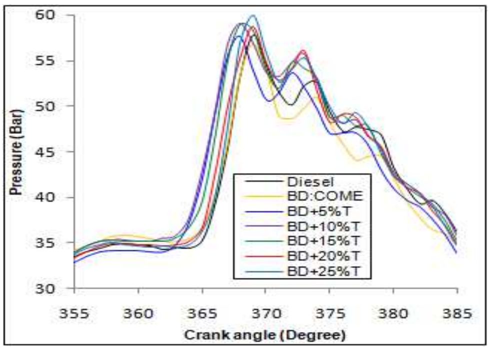

Figure 8: Pressure Variation with Crank Angle at 25% Load

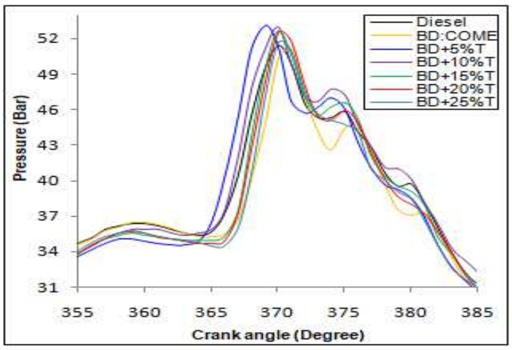

Figure 9: Pressure Variation with Crank Angle at 50% Load

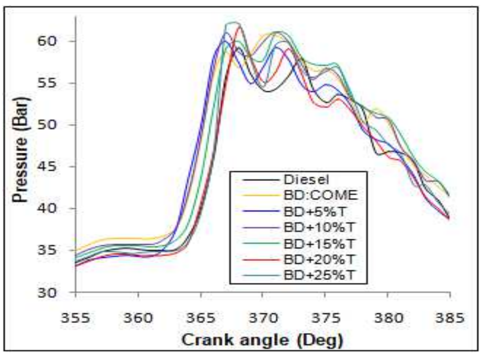

Figure 10: Pressure Variation with Crank Angle at 75% Load

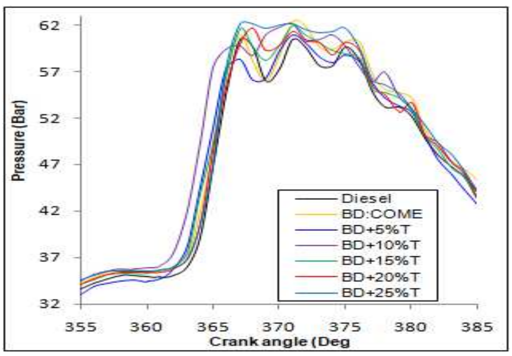

Figure 11: Pressure Variation with Crank Angle at Full Load

Performance Analysis

Figure **12** shows indicated thermal efficiency with reference to the load on engine. Best performance is exhibited by biodiesel and diesel at lower loads. Better thermal efficiency is generated by biodiesel at all loads. With reference to equivalence ratio for the fuels tested, it has increased with increase of triacetin in the blend, but the increase is comparatively lower than that when compared to diesel and biodiesel. This may be due to lower calorific value of fuel and higher boiling point of triacetin additive. Except the abrupt increase of differential pressure in combustion for 25% triacetin blend fuel, all other parameters exhibited uniformity as shown in Figure **13** with load on the engine indicating the maximum blend fuel percentage one can try up to. For 10% triacetin blend fuel, the Figure **14** and table **1** depicts the better performance in the generation of peak combustion pressure, mean effective pressure and its parameters near to TDC, as compared to other fuels at maximum load on the engine. Production of peak pressure near to TDC can produce maximum power by exerting more force for longer period on the piston in expansion stroke. The 10% triacetin blend fuel yielded comparatively better thermal efficiency curve at higher loads.

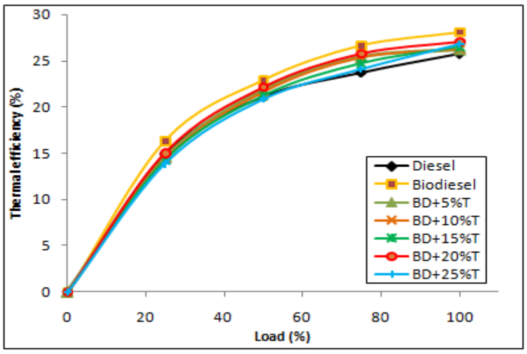

Figure 12: Thermal Efficiency vs. Load

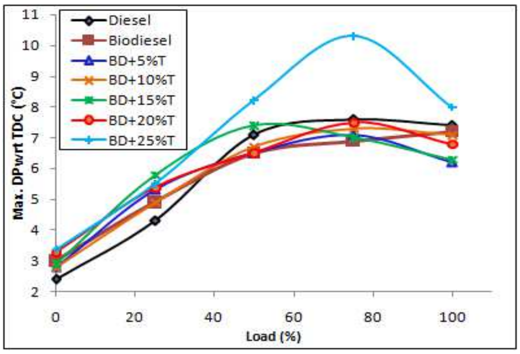

Figure 13: Variation of Max. DP wrt TDC vs Load

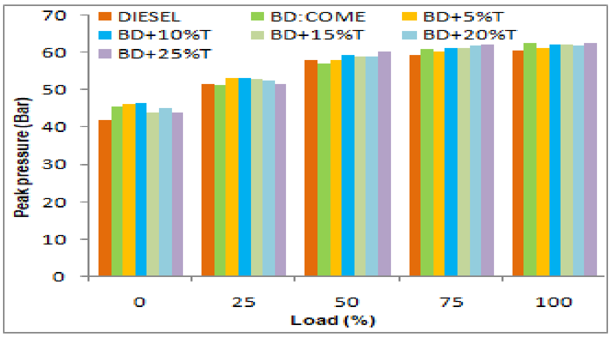

Figure 14: Peak Pressure Variation vs. Load

Table 1: Full Load combustion Parameters

S. No	Fuel	I P (hp)	Imep (bar)	Peak pr.	PP w.r.t to TDP	Max. DP
1	Diesel	5.17	7.5	60.5	+10	7.4
2	Biodiesel	4.97	7.2	61.9	+10	6.3
3	95%B+ 5%T	4.37	6.3	60.9	+10	6.2
4	90%B+10%T	4.95	7.2	62.1	+9	7.1
5	85%B+15%T	4.78	6.9	61.9	+10	6.3
6	80%B+20%T	4.3	6.2	60.9	+7	7.9
7	75%B+25%T	4.56	6.6	63.6	+12	7.4

Vibration Analysis

Figure 1**5** indicate the average spectrum values of the engine cylinder run at different loads, in which 10% triacetin blend fuel at full load generated lowest vibration levels at the points defined. The time waves and the wave forms were recorded on the cylinder head and in the explosion stroke and the obtained graphs were represented against pressure signature, in order to study the combustion details in the cylinder for all blend fuels. The time waves of diesel and 10% triacetin blend fuel are shown in figures **16** and **17** with amplitudes of knocking frequencies. This indicates that at 10% triacetin blend, the knocking amplitude is minimum for the reading obtained on the engine cylinder head, in radial direction and in line crank shaft. The direction is chosen with a view that there won't be mixed effect like piston slap in other radial direction and thrust transfer to the piston in the vertical direction, and thus knocking can be fully realized in the direction inline crank. This plotting is based on nullifying the delay period between the peak pressures generated in the combustion chamber to the maximum vibration peak in the time wave form, picked up from the explosion stroke. This gives a better picture of understanding the ignition propensity for different blend fuel combinations of biodiesel with triacetin. Figure **18** envisages the mean effective pressures (mep) for diesel and biodiesel at full load operation of engine falls in the knocking zone, and for triacetin blend fuels, the mep fall below 6.5bar, and hence no severe knocking at 1500rpm. The knocking frequencies are varying with little margin around 6500Hz, because of the combustion temperature variation with respect to the blend fuel combination of triacetin. The increase in delay period can be ascertained from *0.20ms to 1.70ms* for 5% to 25% triacetin blend fuels, and the figures shown **19** to **21** are diesel, 10% and 25% triacetin blend fuels. There is simultaneous rise in the engine vibration after the start of ignition with respect to increase in triacetin percentage. *The knocking condition of the engine along* with the vibration acceleration is reflected for 25% triacetin blend fuel as shown in Figure **21**, and about 40g amplitude rise is coinciding with the differential pressure rise as shown in Figure **13** and table **1**, whereas 10% triacetin blend (Figure **17**) exhibit smooth combustion with pure harmonic reduction in explosion stroke that eliminating frequencies of mixed nature. The time wave coincides exactly with the pressure variation in synchronous exhibition of pressure exciter and vibration wave generation signatures.

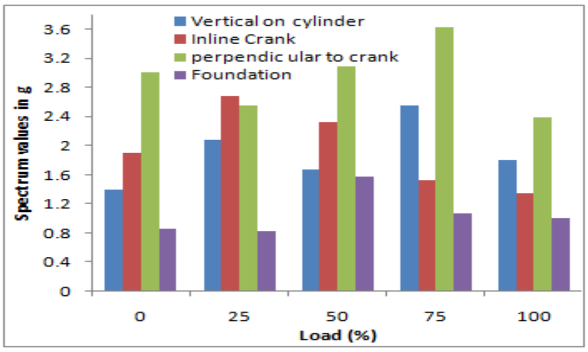

Figure 15: Spectrum Values with Load for 10%Triacetin

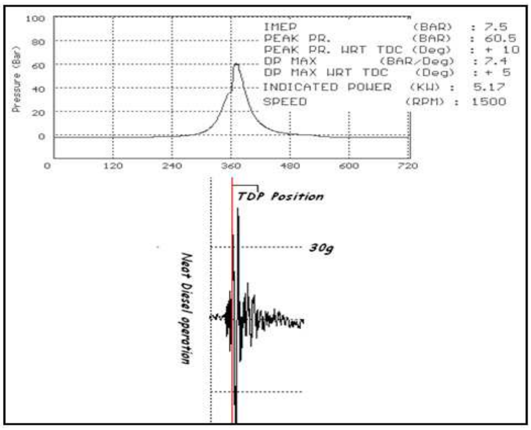

Figure 16: Time Wave Recorded Vertical on Cylinder head during Explosion Stroke at Full Load for Diesel Fuel

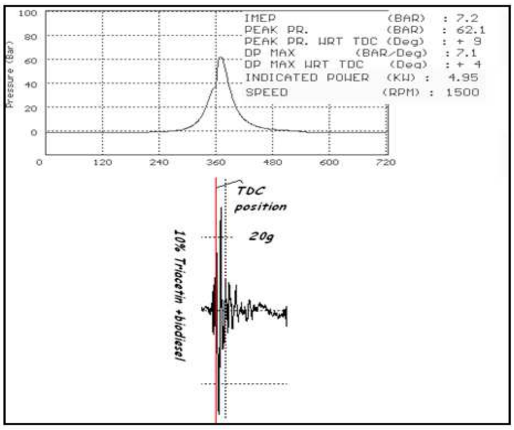

Figure 17: Time Wave Recorded Vertical on Cylinder head during Explosion Stroke at Full Load for Blend Fueld with 10% triacetin and 90% bio-diesel

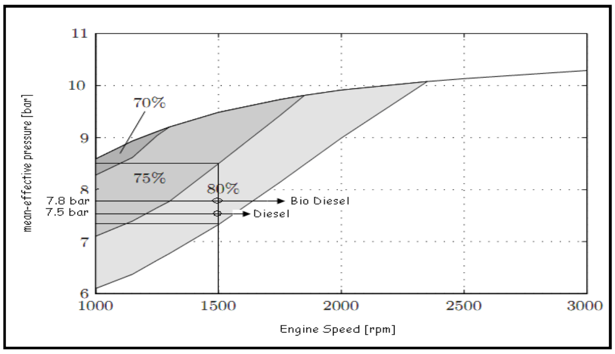

Figure 18 : Full-Load Curve and Knocking Operating Regions under the Assumption for Different Burnt Mass Fractions 'X B'

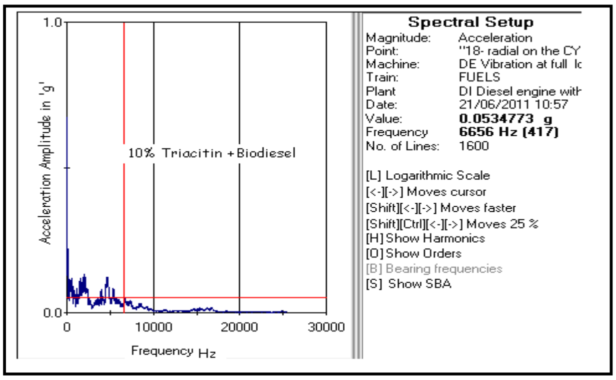

Figure 19: FFT Spectrum Indicating Knocking Frequency and Acceleration Amplitude in the Radial Direction of Cylinder for Neat Diesel Application

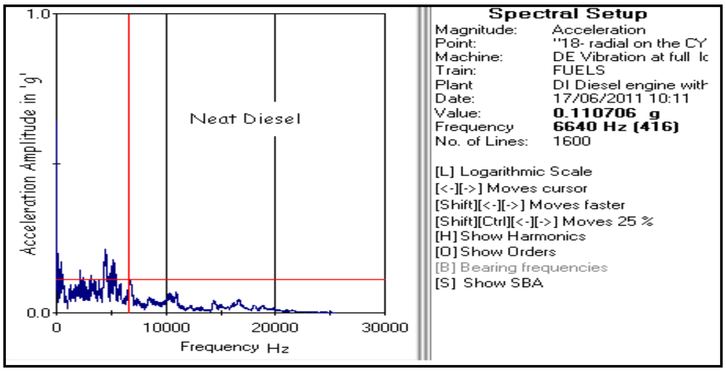

Figure 20: FFT Spectrum Indicating Knocking Frequency and Acceleration Amplitude in Radial Direction of the Cylinder for 10% Triacetin + 90% Biodiesel Blend Fuel Application

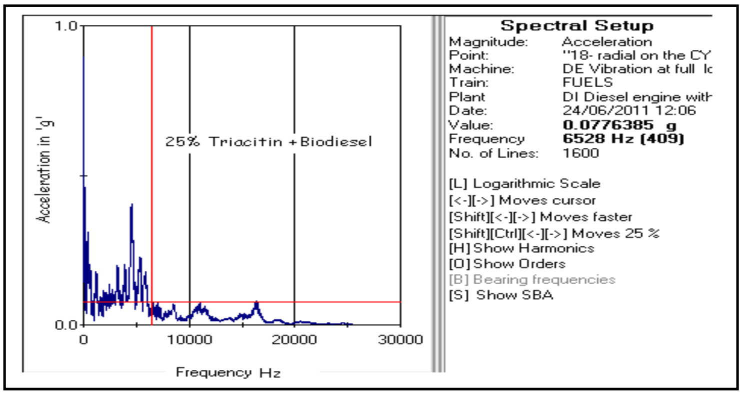

Figure 21: FFT Spectrum Indicating Knocking Frequency and Acceleration Amplitude in Radial Direction of the Cylinder for *25%* Triacetin + *75%* Biodiesel Blend Fuel Application

CONCLUSIONS

Experiments were conducted with neat diesel, COME and COME with Triacetin **[$C_9H_{14}O_6$]** additive blend fuels at 5%, 10%, 15%, 20% and 25% by volume on DI diesel engine. The general performance, combustion, vibration results of the engine are compared with diesel fuel. The conclusions drawn are as follows :

- The blend fuels with Triacetin produced IMEP less than 6.5 bar, eliminating them from the knocking zone. The 10% triacetin blend, even though produced 7.2 bar IMEP can be regarded as safe, since it is marginally below the IMEP ranges of diesel and biodiesel in the 80% burnt mass fraction zone at 1500 rpm.
- For this particular engine cylinder dimensions, the knocking frequency was calculated taking into consideration of the overall combustion temperature as 2000^0K. Knocking level is assessed from the FFT graphs obtained by the engine vibration recorder. The readings on the cylinder head, in radial direction and in line to the crank axis has been chosen to quantify the amplitudes at knocking frequencies. It is understood that 10% blend of triacetin with biodiesel produced lowest amplitude at the knocking frequency around 6,500Hz.
- The delay period is increasing with increase of triacetin percentage in blend fuel, but at 25% of triacetin with biodiesel blend, there is abrupt rise in the cylinder vibration indicating knocking condition of the engine. This is also coinciding in pressure-crank angle plots of 25% triacetin blend fuel, with abrupt differential pressure rise.

- The implicit parameter in Thermal Efficiency is Calorific Value, which decreases with the increase in fuel consumption, as the Calorific Value of Triacetin is comparatively lesser. The 10% triacetin blend fuel yields better thermal efficiency curve at higher loads.

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